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Accounting process-related CO_2 emissions from global cement production under Shared Socioeconomic Pathways

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ABSTRACT

Cement production is the main source of industrial process-related CO_2 emissions, taking up approximately half of total industrial process-related CO_2 emissions. However, limited research has investigated the process-related CO_2 emissions from global cement production, in particular, has not taken into account the impacts of dynamic socio-economic development context. This study aims to explore the trajectory of industrial process-related CO_2 emissions in the cement industry under different Shared Socioeconomic Pathways (SSPs), to provide more evidence for the existing climate change integrated assessment analysis. By investigating the relationship between per capita GDP and per capita cement production process-related CO_2 emissions drawing on the historical data during 1950–2014 in 31 developed countries, the cement production process-related CO_2 emissions from 175 countries in 12 regions in the world during 2015–2100 under five SSP scenarios are given here. The results show that the largest amount of global cumulative cement process-related CO_2 emissions would be 45.45 billion tons under SSP3 scenario. The countries that contribute the most to the global cumulative cement production process-related CO_2 emissions from 2015 to 2100 are India, China, Nigeria, United States of America and Pakistan.

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1. Introduction

As the core building materials, cement is demanded and produced almost in all regions of the world, and the cement manufacturing industry is one of the main contributors to industrial CO_2 emissions following power industry, which account for 5% (Chen et al., 2010; Mikulčić et al., 2013; WBCSD and IEA, 2010) to 7% (Benhelal et al., 2013; Chen et al., 2010) of global anthropogenic CO_2 emissions. It is a remarkable fact that process-related CO_2 emissions are a vital part of total emissions in cement industry that cannot be ignored, which are about 50% in total (Bosoaga et al., 2009; Mahasenan et al., 2003). The process-related CO_2 emissions from cement production refer to the CO_2 emissions generated by raw material decomposition during the clinker burning process (Ke et al., 2013), which mainly come from the $CaCO_3$ decomposition when heated (CSI, 2011; Ke et al., 2013; Shen et al., 2014; Wang et al., 2013). As shown in Fig. 1, among the total emissions from the industrial sectors (excluding power industry) which accounts for approximately 20% of global carbon dioxide emissions (IEA, 2016), apart from direct emissions related to energy consumption and indirect emissions coming from electricity consumption, there is a large amount of emissions emitted from industrial production process (about 20%), such as cement production, chemical production, lime production, etc (IPCC, 2014). Therein, industrial process-related CO_2 emissions from the cement production take up the largest proportion, which are up to 52% (IPCC, 2014). The existing analysis simulating future greenhouse gas emission path, more focused on projecting the GHG emissions caused by energy consumption and non-energy consumption from land use, however, have not paid enough attention to the industrial process-related CO_2 emissions or simply project it according to a rough way such as assuming the industrial process-related CO_2 emissions are in proportion to the level of the activities (such as outputs)

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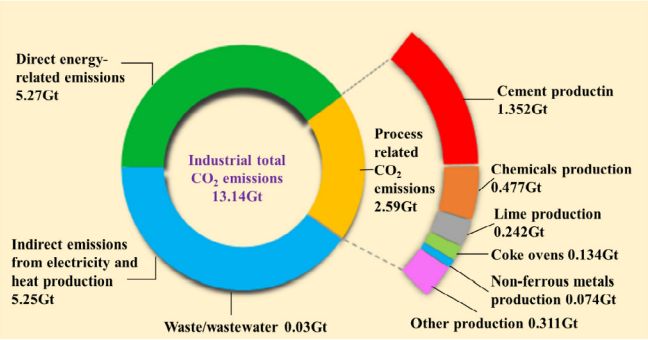

Fig. 1. Industrial carbon dioxide emission sources in 2010. Note: The industrial total CO_2 emissions in this figure do not include the emissions from electricity generation sector. Indirect emissions from electricity and heat production here are related to the electricity and heat consumption in industrial sectors (except power sector). The figure is designed by the authors and data source is from IPCC (2014).

(Fujimori et al., 2017). Alongside further economic development and urbanization, the emissions from cement sector are likely to increase in the future if no interventions are implemented. Therefore, it is very necessary to examine how much the process-related CO_2 emissions will be in the cement industry in addition to the emissions related to energy consumption.

In order to anticipate future global and regional climate change, greenhouse gases emissions must be framed under different scenarios (so-called emission scenario). Emissions scenarios are usually designed based on a set of assumptions for socio-economic and technological factors (Nakicenovic and Swart, 2000). IPCC has presented a new generation of socio-economic scenarios. Combing with the potential socio-economic development pathways in the future, different emission scenarios are developed by the integrated assessment models (e.g., AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, ReMIND-MAGPIE, and WITCH), known as the "Shared Socioeconomic Pathways (SSPs)" (Moss et al., 2010). Details of the concepts and structures of the scenarios are discussed by O'Neill et al. (2012), O'Neill et al. (2014), and Vuuren et al. (2014). SSPs scenarios unite radiation forcing and social-economic development conditions into one human development mode, presenting the different basic scenarios in human society's ability to mitigate and adapt to climate change. Compared with the previous radiative forcing and emission scenarios, more emphasis has been placed on the changing trajectories of population growth, economic development, technological progress, environmental conditions and so on. Five SSPs scenarios are designed by reflecting different development circumstances and different levels of global challenges to climate change mitigation and adaption shown in Fig. 2, including scenario following a green growth strategy (SSP1) (Vuuren et al., 2012) that has a low level of challenges to not only mitigation but adaptation, a more middle-of-the-road development pattern (SSP2) (Fricko et al., 2016) that has a medium level of challenges to both mitigation and adaptation, further fragmentation between regions (SSP3) (Fujimori et al., 2017) that represents the two extremes in terms of challenges to mitigation and adaptation, an increase in inequality across and within regions (SSP4) (Calvin et al., 2016) that means a high level of challenge to adaptation but low level of challenge to mitigation and, fossil fuel based economic development (SSP5) (Kriegler et al., 2014) that represents high level of challenge to mitigation and low to adaptation (O'Neill et al., 2014). For each SSP, the indicators of population, GDP, and technical productivity in different countries are quantified, and a qualitative description of the level, speed and direction of social and economic development around the world are provided.

Considering the uncertain and dynamic socio-economic contexts in the future, the projection of industrial process-related CO_2 emissions should not be independent from the socio-economic development pathways. Under these contexts, this study aims to explore the trajectory of industrial process-related CO_2 emissions in the cement industry under five Shared Socioeconomic Pathways (SSPs) for different countries around the world, so as to support the existing methods and make the climate change assessment more comprehensive. To this end, the mixture regression model is adopted to identify the relationship between socio-economic indicators and cement production process-related CO_2 emissions as well as the peaking time, drawing on the historical panel data from 31 developed countries from 1950 to 2014. The results are further used to project the process-related CO_2 emissions from the cement industry for majority of global countries (175 countries or areas) until 2100.

This paper is structured as follows. The second section is to summarize the CO_2 emission sources in cement industry. Section 3 introduces the research framework, data related to cement production process-related CO_2 emissions and SSPs, and research methods. Section 4 explains the projection results by country and region. Section 5 concludes the research findings and implications.

2. CO_2 emission sources in cement industry

The cement industry is a typical industry with both emissions from fossil fuel combustion and process-related emissions. As shown in Fig. 3, the process of cement production generally includes three main stages (Shen et al., 2014): raw material preparation, clinker burning and cement grinding. In these production phases, carbon dioxide emissions can be divided into two parts: One is the direct emissions (90%) resulting from fossil fuel combustion and decomposition of $CaCO_3$ when raw materials calcining; and the other part is the indirect emission (10%) caused by electricity consumption (CSI, 2011). No matter what kind of production technology selected, the main equipment for cement manufacturing includes two grindings and one kiln. Two grindings mean the raw material grinding and the cement grinding; and a kiln refers to the cement kiln, which contains vertical kiln and rotary kiln. The direct CO_2 emissions are mostly discharged in the cement kiln.

In summary, CO_2 emissions from the whole cement industry can be expressed as equation (1):

$$\begin{aligned}\text{Total } CO_2\ emissions &= CO_2\ emissions_{\text{direct}} + CO_2\ emissions_{\text{indirect}} \\ &= \Big(CO_2\ emissions_{\text{process}} \\ &\quad + CO_2\ emissions_{\text{fuel combustion}}\Big) \\ &\quad + CO_2\ emissions_{\text{electricity consumption}}\end{aligned} \tag{1}$$

Carbon dioxide emissions from fossil fuel combustion are defined as fuel emissions (Gao et al., 2015). During the process of clinker burning, large amounts of fuels are burned to provide high temperature for the material decomposition and then output CaO which is the main component of clinker. The preferred method for calculating fuel emissions is based on the fuel consumption structure, low calorific value of the various fuels and the emission factors for the corresponding fuel. Hence, fuel emissions can be reduced by improving energy efficiency and using fuel replacement materials. The indirect carbon dioxide emissions from electricity consumption can be defined as "electricity emissions" (Shen et al., 2014), which contains the carbon dioxide emissions embedded in the production process of consumed electricity in each phase.

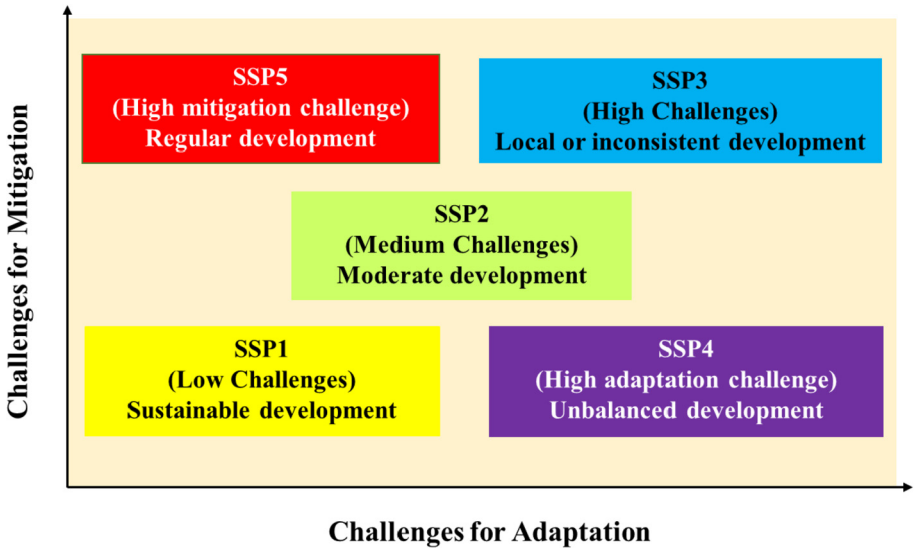

Fig. 2. Characteristics of SSPs. Note: The horizontal axis indicates that the level of challenges to adaption is rising from left to right, and the vertical axis represents that the level of challenges to mitigation is increasing from bottom to top. This figure is designed by authors referring to O'Neill et al., 2014.

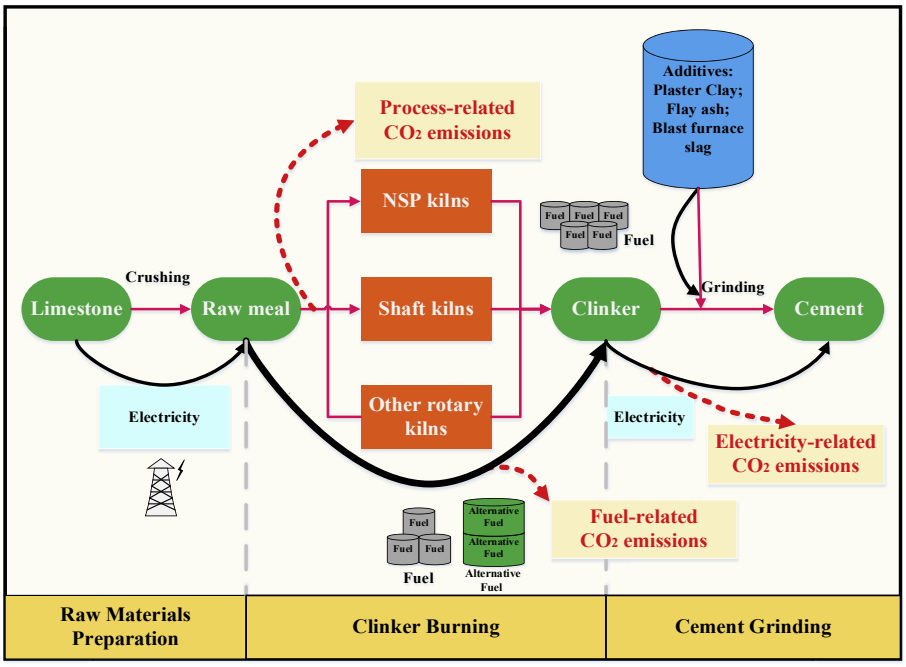

Fig. 3. Flowchart of cement production.

The carbon dioxide emissions generated by material decomposition during the clinker burning process are defined as process-related CO_2 emission (Ke et al., 2013), which mainly come from the $CaCO_3$ decomposition when heated and it is the main component contained in the raw materials (CSI, 2011; Ke et al., 2013; Shen et al., 2014; Wang et al., 2013). Process-related CO_2 emissions are determined by the amount of carbonate in the raw materials (Rattanashotinunt et al., 2013) and the quantities of clinker (Gao et al., 2015; Liu and Li, 2010). At present, countries in the world generally use natural limestone to produce cement, which is composed of 98.5% $CaCO_3$ and 1.5% $MgCO_3$ (He, 2009).

In regards to the methods of calculating cement production process-related CO_2 emissions, some organizations and developed countries have formed a relatively mature accounting system. There are three mainstream international systems and standards for accounting process-related CO_2 emissions until now: (1) Intergovernmental Panel on Climate Change published the 'Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories', 'National greenhouse gas inventory guidelines for good practices and uncertainty management (2000)' and '2006 IPCC Guidelines for National Greenhouse Gas Inventories', in order to assist the high contracting nations of 'The United Nations Framework Convention on Climate' to make National Greenhouse Gas Inventories; (2) World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) promulgated 'Greenhouse Gas Protocol' in 2001; (3) The companies that participated the

Cement Sustainability Initiative (CSI) organized by World Business Council for Sustainable Development (WBCSD) reached an agreement named 'CO_2 Accounting and reporting standard for the cement industry' to calculate and report carbon dioxide in 2001. Appendix Table A.1 lists eight reports, including international standards for the calculation of cement production process-related CO_2 emissions and more typical computational systems developed based on the three standards as we mentioned above.

With reference to these reports, it is found that there are two general types of methods for calculating the cement production process-related CO_2 emissions, namely the raw material method and the clinker method. The raw material method calculates the emissions based on the consumed raw material quantities and the emission coefficient of carbonate in raw materials. The clinker method is based on the output of clinker and then the emissions are calculated by the field specific emission coefficients which are based on the material balance of CaO and MgO. These two methods are the same from theoretical viewpoint. The raw material methods are widely used in the United States and Japan. While the clinker method was presented in the National Greenhouse Gas Inventories IPCC Guidelines in 1996. It is not difficult to find that these two methods (i.e., the raw material method and the clinker method) are based on a bottom-up perspective that start from the quantity of raw materials or products. However, to incorporate the impacts of different socio-economic development contexts on the global cement production process-related emissions, a top-down perspective may be more straightforward.

3. Method

3.1. Research framework

The cement production process-related CO_2 emissions greatly depend on the cement demands, particularly the clinker demands which have been mentioned above (Gao et al., 2015; Liu and Li, 2010). Cement as an important building material, its demand has close relationship with country's economic development level indicated by GDP. Some studies have found that the developing trends of cement demand in different countries and regions are similar to an inverted U-shaped relationship by analyzing the historical cement demands in developed countries and regions that have experienced rapid development of the industrialization process (Uwasu et al., 2014). More specifically, when the economy is in the primary stage, or the GDP value is relatively low, the cement demand rises slowly. While with the economy growing rapidly, cement demand increases swiftly. The peak of cement demand arrives after period of large-scale construction, when the economy goes into maturity, or the GDP growth slows down, the cement demand will gradually decline (Uwasu et al., 2014). By analyzing the changes in per capita cement demand in developed countries and regions, it is found that when the per capita GDP reaches a certain value, cement demand tends to be saturated, implying that the infrastructure construction of a country or region is basically completed and urbanization rate is high enough (Uwasu et al., 2014).

Given that cement production process-related CO_2 emissions are directly relevant to cement demand, it is plausible to assume that GDP and cement production process-related CO_2 emissions might be interrelated. To verify our assumption, we first conduct the scatter analysis by employing the historical data of the cement industry process-related CO_2 emissions during 1950–2014 in 38 developed countries. Mixture regression analysis is further adopted to quantify the relationship between GDP per capita and cement production process-related CO_2 emissions based on the identified trends from scatter analysis. The estimation results are subsequently used to project the process-related CO_2 emissions for different countries (175 countries or areas) around the world during 2015–2100 with the consideration of uncertain socioeconomic pathways. The involved countries are grouped into 12 regions for explanation in this study (shown in Appendix Table A.4), so as to display the development characteristics and emission-reduction intention of different countries, and meanwhile to be consistent with the division of regions in SSP database and support the existing mainstream integrated impact assessment analysis. Finally, the cement production process-related CO_2 emissions in 175 countries or areas located in 12 regions under five socioeconomic pathways that represent different challenges to climate change mitigation and adaption are derived from a global angle. The research framework is shown in Fig. 4.

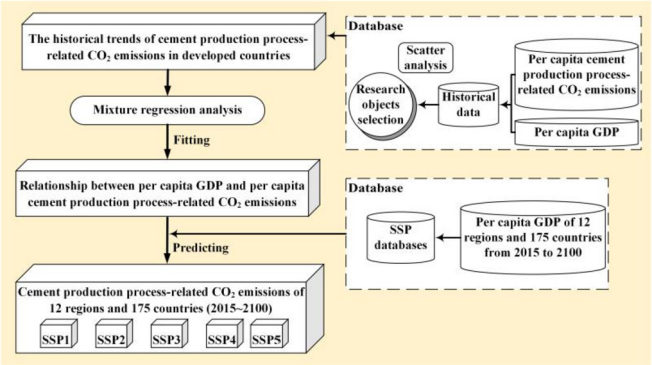
The historical trends of cement production process-related CO_2 emissions in developed countries
Mixture regression analysis
Fitting
Relationship between per capita GDP and per capita cement production process-related CO_2 emissions
Predicting
Cement production process-related CO_2 emissions of 12 regions and 175 countries (2015~2100)
SSP1
SSP2
SSP3
SSP4
SSP5
Database
Scatter analysis
Research objects selection
Historical data
Per capita cement production process-related CO_2 emissions
Per capita GDP
Database
SSP databases
Per capita GDP of 12 regions and 175 countries from 2015 to 2100

Fig. 4. Research framework.

3.2. Data

In this study, two main datasets are employed: data of cement production process-related CO_2 emissions and data of Shared Socioeconomic Pathways (SSPs).

(1) Data of historical process-related CO_2 emissions from cement production

The data of process-related CO_2 emissions from cement production is obtained from the Oak Ridge National Laboratory.[1] The database includes the historical data of cement production process-related CO_2 emissions in global 220 countries until the year of 2014, which is calculated by the quantity of cement produced and the conversion factor that was obtained by dividing the molar mass of carbon by the molar mass of calcium oxide and multiplying this quotient with the average fraction of calcium oxide contained in cement. We select 44 developed countries and regions listed in the Human Development Report 2010 published by the United Nations Development Program (UNDP) as research objects at first, among them, Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, United States, and United Kingdom (28 countries) are developed economies in Organization for Economic Co-operation and Development (OECD); Andorra, Bahrain, Singapore, Barbados, Brunei, Cyprus, Estonia, Israel, Liechtenstein, Malta, Monaco, Qatar, San Marino, Slovenia, UAE, and Hong Kong (16 countries or regions) are

[1] Source: Tom Boden and Bob Andres (Oak Ridge National Laboratory); Gregg Marland (Appalachian State University).

developed economies in non-OECD organizations. However, considering that the statistical data on the cement production process-related emissions in Monaco is included in France, San Marino is included in Italy, and Hong Kong is included in China and also the emission data in Andorra, Liechtenstein and Malta is zero which cannot be included in our dataset, hence, we finally selected 38 countries as research objects for the scatter analysis from 1950 to 2014. Specially noted that the initial year of some object countries are based on their earliest available data such as Qatar, Barbados and so on.

In order to investigate the relationship between economic level and process-related CO_2 emissions during cement production, the historical GDP data and population data are further required. Historical GDP data is from PWT8.1 (Zeileis, 2013). PWT8.1 provides three real GDP, namely, the real GDP of the expenditure method, the real GDP of the income method, and the real GDP calculated based on the country's growth rate. According to PWT8.1, the real GDP of the expenditure method can be used to compare the long-term living standard between countries, which is consistent with the purpose of this study and therefore, this paper chooses the calculated value of purchasing power parity (PPP, 2005 constant) in view of the fact that the exchange rate between the different countries will underestimate the output level of developing countries (Samuelson and Nordhaus, 2009). Population data for each country is referring to the historical statistics of the countries from the 1950s to 2014 in *the World Population Outlook 2015* published by the United Nations.

Taking the per capita GDP as the horizontal ordinate and the per capita cement production process-related emissions as the vertical ordinate, we drawn a scatter diagram for each of the above 38 world recognized developed countries (shown in Fig. 5). It can be found that the per capita cement production process-related emissions in the first 31 highly industrialized countries in Fig. 5 will increase with the growth of per capita GDP. When per capita GDP grows to a certain value, the per capita process-related CO_2 emissions from cement production will reach the peak, and then shows a slow decline with slow growth of per capita GDP. There is a nonlinear inverted U-shaped relationship between per capita GDP and per capita cement production process-related CO_2 emissions. Whereas, for the last seven countries (Poland, Qatar, Czech Republic, Barbados, Bahian, United Arab Emirates, Slovakia, Brunei) in Fig. 5, because of the small amount of statistics and small scale of the country, no evident relation between economic level and process-related CO_2 emissions in cement industry is revealed. Consequently, we exclude these seven countries from the dataset used for our study.

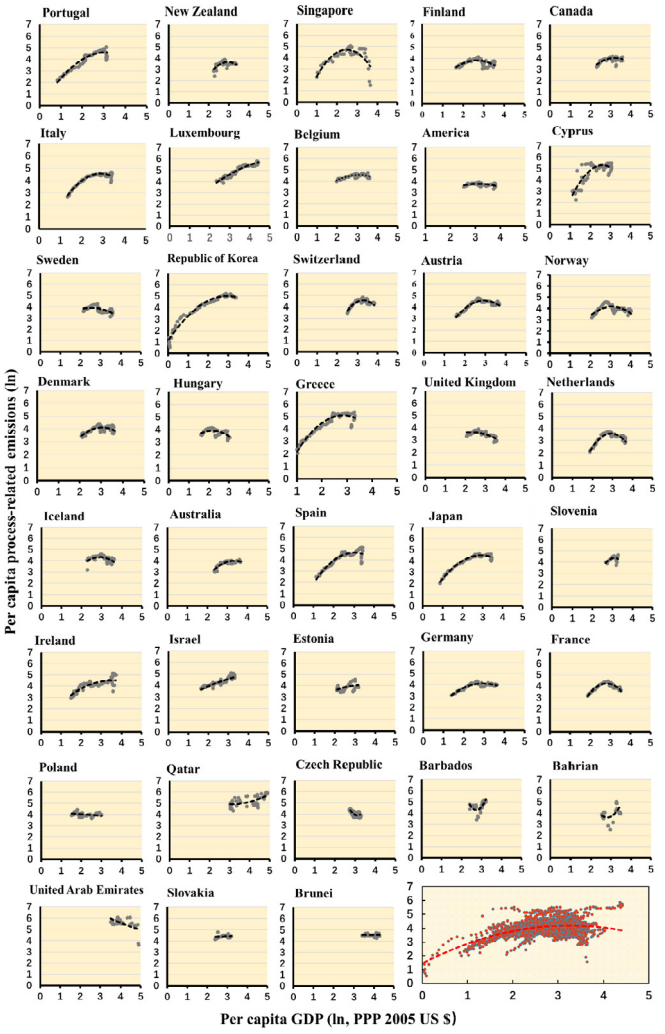

Fig. 5. Scatter diagrams of per capita GDP and per capita process-related emissions from cement production by country. Note: The vertical and horizontal coordinates are logarithmic values.

(2) **Data of Shared Socioeconomic Pathways**

GDP and population for 175 countries in the world from 2015 to 2100 under SSP1-SSP5 scenarios are coming from the projections results developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR) in the SSP database.[2] The data for future GDP and population in the database is presented at a span of 10 years. This study will adopt a linear approach to decompose the data to each year to account for the countries' total cement production process-related CO_2 emissions from 2015 to 2100.

Fig. 6 shows the per capita GDP changes under the SSP1-SSP5 scenarios. It can be seem that different levels of challenges to climate change mitigation and adaptation significantly influence the economic development in most of the countries. From a regional perspective, United States of America (USA) has the largest per capita GDP in the early stages of the five scenarios, and as the future human society's coping ability to mitigation and/or adaptation to climate change alters, the growth trend and increment of per capita GDP in different regions will also change. Per capita GDP in all five scenarios is on the rise, but their respective growth rates and trends are not the same. In fossil fuel based economic development (SSP5) scenario, the increment of per capita GDP in the 12 regions is the largest, and the development speeds in the 12 regions are basically the same. In a more middle-of-the-road development pattern (SSP2) and further fragmentation between regions (SSP3) scenarios, the overall trends and peak points of per capita GDP are basically the same, but the growth range and rate in the SSP2 scenario after 2070 is larger than those of SSP3. In a green growth strategy (SSP1) scenario, each region shows a rapidly growing state. And in an increase in inequality across and within regions (SSP4) scenarios, the growth rates of per capita GDP are relatively high in United States of America (USA), Japan (JPN) and the European Union (EU), and slow in the Middle East and Africa (MAF) and Asia (AISA). The growth rates in the rest of regions are relatively uniform. It can be seen that per capita GDP are different in different regions and in different scenarios with specific characteristics.

[2] Source: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

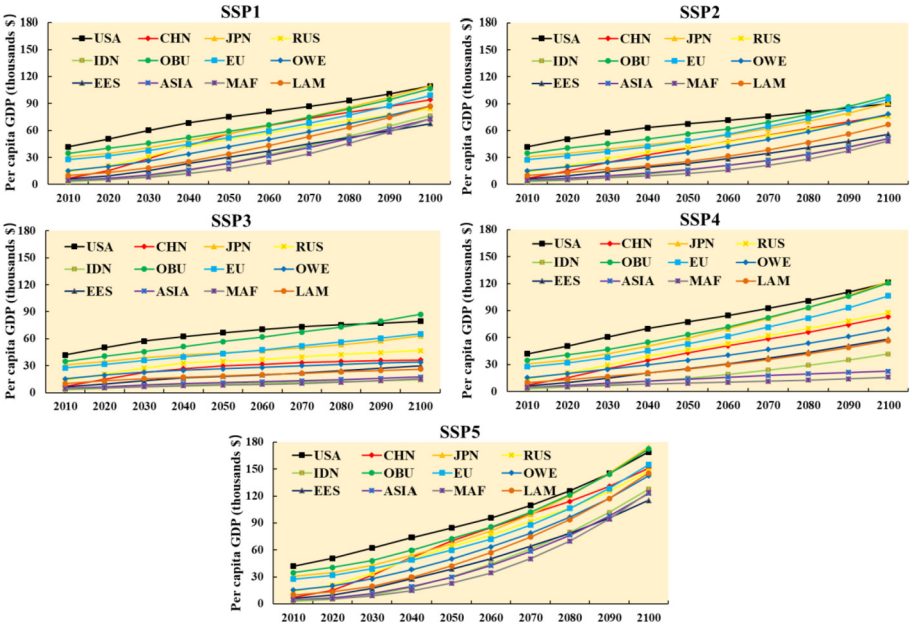

Fig. 6. Per capita GDP trend under SSP1 - SSP5 scenarios.

3.3. Model for estimating future process-related CO_2 emissions from cement production

To quantify the relationship between per capita GDP and per capita cement production process-related emission and find the peak point, we use mixture regression analysis of non-equilibrium panel data from 31 developed countries and regions from 1950 to 2014, with per capita cement production process-related CO_2 emissions (logarithmic) as the dependent variable and per capita GDP (logarithmic) as explanatory variables. Using logarithmic form, we can reduce the volatility of the data on the one hand, and eliminate its heteroscedasticity on the other hand. The initial year of each object country is based on their earliest available data, and the shortest time span among these countries is more than 20 years, with a total of 1847 observations. Here, we assume that the change of cement production process-related CO_2 emissions in less developed countries may follow the average path of developed countries, and the global trend would fit most of the countries enlightened by the similar trend revealed in the scatter analysis.

In this paper, to represent the nonlinear relation, we specially incorporate a square term of GDP per capita, the logarithmic linear model of the quadratic function of per capita production process-related CO_2 emission is given as follows:

$$\ln(c_{it}) = \beta_0 + \beta_1 \ln(y_{it}) + \beta_2(\ln(y_{it}))^2 + \varepsilon_{it} \quad (2)$$

where, i and t refer to the country and year respectively; c_{it} represents the per capita cement production process-related CO_2 emissions in country i at year t; y_{it} measures the economic development of country i at year t, expressed by per capita GDP; β_k is the coefficient of the kth explanatory variable; ε_{it} is an error term following the independent distribution *(i.i.d)* of the classical econometric hypothesis. In this paper, the model is fitted by the panel data mixture regression, assuming that all individuals have the same regression equation, and there is no individual effect. Its implication is that we can fit a curve of cement production process-related CO_2 emissions that is applied to every country in the world based on the conditions of developed countries with high levels of industrialization, and predict the emissions of each country in the future by assuming that the developing countries progress in the track of the developed countries.

Since the panel data is composed of time series data and cross-section data, the analysis based on the panel data may produce false regression if the time-series dimensionality of the panel data is unstable. Therefore, the unit root test and the cointegration test should be carried out before the spatial regression analysis. If some variables have a unit root and the other variables do not, the regression will be false (Wooldridge, 2000). In this study, the panel data are tested to check the presence of unit roots, employing commonly used asymptotically distribution-free(ADF), Levin, Lin and Chut (LLC) (Levin et al., 2002) and Phillips-Perron (PP) (Perron, 1987) tests.

4. Results and discussions

The unit root test and the cointegration test results show that all the original sequences are non-stationary sequences, and their first-order differences are stationary sequences, therefore the original sequences are all first-order single sequences (Appendix Table A.2). At the same time, we adopt the Johansen cointegration technique to test the cointegration relationship between variables. The results indicate the null hypothesis that there is no cointegration relationship between variables can be rejected at the significant 5% level, hence, the regression analysis can be performed (Appendix Table A.3).

The parameters of the model obtained by using the mixture regression analysis are shown in Table 1. The explanatory variables

Table 1
Estimation results of per capita process-related CO_2 emissions in cement industry.

Variable	Parameter	Estimated coefficients
$\ln(y_{it})$	β_1	2.06[a]
$(\ln(y_{it}))^2$	β_2	−0.327[a]
Constant	β_0	0.987[a]

Notes: Sample size = 1847, Adj R-squared = 0.337.
[a] Indicates statistical significance at a level of 1%.

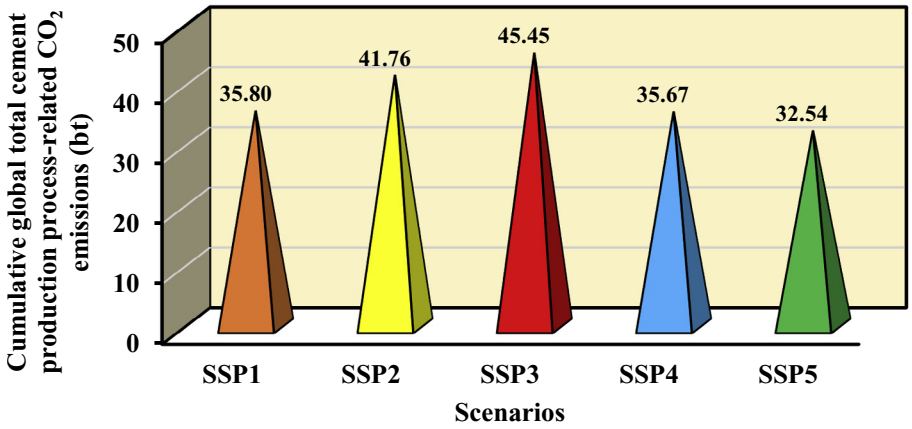

Fig. 7. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP1-SSP5 scenarios.

are significant at 1% level, and the accuracy of the model is acceptable. It is found that significant relationship between cement production process CO_2 emissions and GDP is observed. Thus, we further use this model to project the cement production process-related CO_2 emissions under SSP1-SSP5 scenarios in each country and region of the world from 2015 to 2100.

4.1. Total cement production process-related CO_2 emissions for different countries and regions in SSP1-SSP5 scenarios

Comparing the total cement production process-related CO_2 emissions in five SSP scenarios (as shown in Fig. 7), we find that the emissions are significantly different. In case of the SSP3 scenario (both challenges to adaptation and mitigation are high), the cumulative cement production process-related CO_2 emissions are the highest, reaching 45.45 billion tons. It is followed by the emissions in SSP2 in which challenges to adaptation and mitigation are of medium and low level. Besides, cumulative global cement production process-related CO_2 emissions in SSP1 (35.80 billion tons) and SSP4 (35.67 billion tons) are in the third and fourth place respectively which are larger than the emissions in SSP5 (32.54 billion tons). Combining with the estimation results of the cumulative global CO_2 emissions from 2015 to 2100 predicted by integrated assessment models (e.g., AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, ReMIND-MAGPIE, and WITCH) (Calvin et al., 2016), it is calculated that the cumulative global cement production process-related CO_2 emissions derived from this study account for 0.5%–2% in the total CO_2 emissions. This proportion is in a reasonable range compared with the proportion of 2% in 2010 (IEA, 2016).

The top 10 countries with highest process-related CO_2 emissions under each SSP scenario are listed in Table 2 and shown in Fig. 8 and Fig. A.1-A.4. It shows that the cumulative cement production process-related CO_2 emissions in India and China are all in the top two places, and that the sum of the total emissions of these two countries have reached 58%–61% of the world's total emissions. At present, Chinese cement production and the process-related CO_2 emissions are ranked first in the world. In the coming years, India will surpass China and become the country with the largest cement process-related CO_2 emissions. Other countries such as Nigeria, United States of America, Pakistan, Indonesia, Brazil, Bangladesh, Mexico, the Philippines, Egypt, and Russia are countries with higher emissions. But the emission paths are also not the same in different scenarios.

Taking SSP3 scenario as an example, the cumulative cement production process-related CO_2 emissions in 12 regions (2015–2100) are shown (Fig. 8), and the results of the remaining four scenarios are shown in the appendix (Fig. A.1-A.4). From a regional perspective, the cumulative cement production process-related CO_2 emissions of Middle East and Africa (MAF, including 65 countries) are at the top place, India normally rank at the second place, and put in the third and fourth place in Asia (AISA, including 27 countries) and China. The cement production process-related CO_2 emissions of Latin America (LAM) and the European Union (EU) follow closely and their total emissions cannot be ignored. On the contrary, the cumulative cement production process-related CO_2 emissions of Other Branches of Umbrella Group (OBU) and Japan in five scenarios are in the last places which have little contribution to global emissions.

4.2. Trends and proportion of cement production process-related emissions in 12 regions

Different areas have different trends and proportions in SSP1-SSP5 scenarios (Fig. 9). In the SSP3 scenario, the total volume continues to grow and does not reach its peak. The reason might be that the per capita GDP in SSP3 scenario which has a high level of challenge for adaption and mitigation, keeps a low upward trend shown in Fig. 6, thus the demand for cement is not saturated until 2100 and the production process-related CO_2 emissions keep rising. In the SSP3 scenario, apart from United States of America (USA), China (CHN), the European Union (EU), Other Branches of Umbrella Group (OBU) and Japan (JAN), the emissions of the rest regions continue to grow and do not reach the peak by 2100, contributing more to the global cement process-related emissions year by year. In the SSP4 scenario, the cumulative amount emissions increase first and then flatten. This might be caused by the joint effect of the slow growth of per capita GDP in regions such as Middle East and Africa (MAF) and a relatively fast growth of per capita GDP in regions such as Other Branches of Umbrella Group (OBU). Emissions from the regions with fast growth of per capita GDP are likely to peak early and subsequently, their decreasing emissions are offset by the increasing emissions of regions with slow growth of per capita GDP. In SSP4 scenario, the emissions in areas such as the Middle East and Africa (MAF) and Asia (AISA) are always on the rise, contributing more to global process-related CO_2 emissions. Except these areas, the amounts have reached the peak early or late before 2100. In the other three scenarios, the figure shows an increase trend followed by a decrease trend, but their peak time are different. The emissions in SSP5 scenario would reach the peak earliest, followed by SSP1 and SSP2 scenarios. In SSP1, SSP2 and SSP5 scenarios, the amount of all regions increases initially and decreases afterwards, and the peak time of emissions in developed areas are earlier than those in developing regions (shown in Fig. 9).

Table 2
Cumulative total cement production process-related CO_2 from 2015 to 2100 of different countries (Unit: Billion tons).

SSP1		SSP2		SSP3	
Nation	CO_2 emissions	Nation	CO_2 emissions	Nation	CO_2 emissions
India	6.72	India	8.23	India	9.31
China	5.02	China	5.78	China	6.95
Nigeria	1.50	Nigeria	1.88	Nigeria	2.10
U.S.	1.50	Pakistan	1.60	Pakistan	1.55
Pakistan	1.30	U.S.	1.60	Indonesia	1.54
Indonesia	1.12	Indonesia	1.34	Brazil	1.40
Brazil	0.99	Brazil	1.18	U.S.	1.30
Bangladesh	0.71	Bangladesh	0.78	Mexico	1.05
Philippines	0.60	Mexico	0.73	Philippines	0.83
Mexico	0.60	Philippines	0.71	Egypt	0.80

SSP4		SSP5	
Nation	CO_2 emissions	Nation	CO_2 emissions
India	7.28	India	6.07
China	5.22	China	4.42
Nigeria	1.80	U.S.	1.53
U.S.	1.30	Nigeria	1.32
Pakistan	1.27	Pakistan	1.19
Indonesia	1.15	Indonesia	0.98
Brazil	1.05	Brazil	0.87
Philippines	0.73	Bangladesh	0.64
Mexico	0.65	Philippines	0.54
Russian Federation	0.57	Russian Federation	0.52

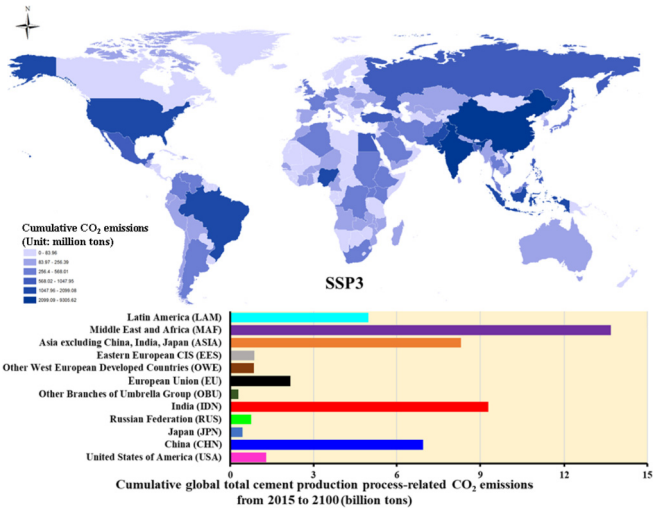

Fig. 8. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP3 scenario. Note: Both the map and bar chart are showing the cumulative cement production process-related CO_2 emissions in the study SSP. Map is for 175 countries and bar chart is for 12 regions.

For instance, the USA and Japan would peak its emissions before 2015 under these three scenarios, which are much earlier than other regions.

From the perspective of regional contribution to global emissions under five scenarios, Middle East and Africa (MAF), Asia (ASIA), India (IDN) and China (CHN) rank the top, contributing substantially to the global cement production process-related CO_2 emissions while other regions such as Other Branches of Umbrella Group (OBU), the United States (UAS), the European Union (EU), Russia (RUS) and Japan (JAN) contribute much less.

4.3. Comparison of total cement production process-related emissions in SSP1 - SSP5 scenarios in different regions

For each region, the trends of cement production process-related CO_2 emissions of five SSP scenarios are different. Fig. 10 shows the trends of CO_2 emissions in SSP1-SSP5 scenarios in each region over time. And the trends mainly can be divided into two categories.

The first category: the cement production process-related CO_2 emissions had reached the peak and shown a continuously downward trend. For instance, the emissions in the European Union (EU), United States of America (USA), Japan (JPN) are all declining under SSP1-SSP5 scenarios but with different emission paths in each region under different scenario. Emissions in Russia (RUS) are declining under four scenarios except in SSP3. For the European Union (EU) and Japan (JPN), the trends in the five scenarios are all in decline and the gaps between them are smaller, indicating that different socio-economic conditions and human development models have slight effect on the cement production process-related CO_2 emissions in these two regions and path of the emissions are basically the same in different scenarios in the future. While the emissions of United States of America (USA) in the five scenarios and Russia (RUS) in four scenarios (except for SSP3 scenario) are also in a downward trend, but the descent rates and the specific emissions have large differences. For example, in United States of America (USA), compared with the other three scenarios, in SSP3 and SSP4 scenarios, the descent rates are more equal and the falling range are larger compared with the other three scenarios, indicating that the general trends of the cement production process-related CO_2 emissions in the two regions are similar but the emissions paths are not the same in different socioeconomic situations in the future. Therefore, different population and economic development level can greatly affect the path of cement production process-related CO_2 emissions.

The second category: continuously rising or rising first and declining afterwards. Fig. 10 shows that the cement production process-related CO_2 emissions in most of the regions are following these two trends among five scenarios. Apart from China (CHN) and Other Branches of Umbrella Group (OBU) for which the emissions decline after reaching the peak in the SSP1-SSP5 scenarios, in the remaining six regions, the emissions in the five scenarios all have two trends: upward or upward first and then downward. Eastern

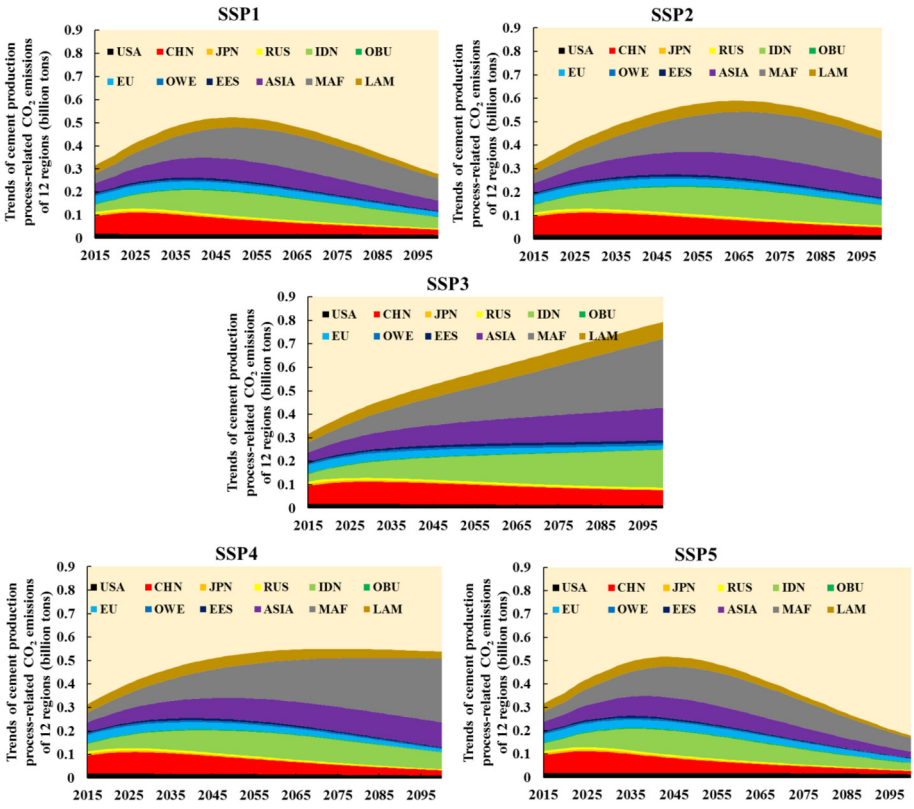
SSP1
SSP2
SSP3
SSP4
SSP5
USA CHN JPN RUS IDN OBU
EU OWE EES ASIA MAF LAM
Trends of cement production process-related CO2 emissions of 12 regions (billion tons)
2015 2025 2035 2045 2055 2065 2075 2085 2095

Fig. 9. Trends of cement production process-related CO_2 emissions of 12 regions in SSP1-SSP5.

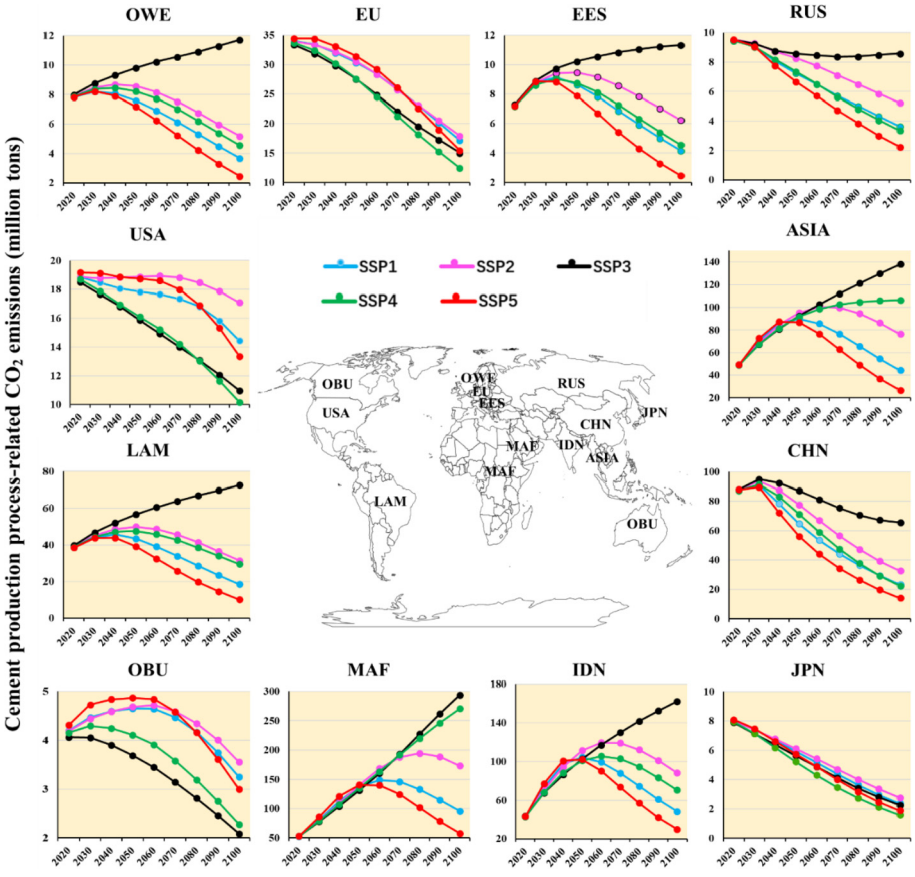

Fig. 10. Cement production process-related CO_2 emissions under SSP1-SSP5 scenarios in 12 regions.

European CIS (EES), Latin America (LAM), Other West European Developed Countries (OWE) and India (IDN) have similar path. In their respective SSP3 (high challenge) scenarios, the total amounts of emissions are all the largest and have been increasing without reaching the peak until 2100. However, the emissions in the four regions (EES, LAM, OWE, IDA) under the other four scenarios (SSP1, SSP2, SSP4, SSP5) decline after achieving the peak in different years, showing that the maximum of process-related CO_2 emissions in the four regions are quite different among SSP1, SSP2, SSP4, and SSP5 scenarios. Apart from SSP3 scenario, emissions in Asia (ASIA), Middle East and Africa (MAF) have been on the uptrend also in SSP4 scenario, illustrating that the SSP4 scenario can boost the economic development of both regions as well as stimulating the cement demand and contribute more cement production process-related CO_2 emissions.

From the perspective of the peaking time, different regions have different development paces in different scenarios, and the contributions to the total amount emissions are inequable at respective times. China (CHN) can achieve the peak of cement emissions by 2030 and Latin America (LAM), Other West European Developed Countries (OWE) can also achieve peak relatively early, probably between 2030 and 2040, indicating that the cement production process-related CO_2 emissions in the four regions will get saturated early, and their contributions to the world's total emissions decline after 2040. However, Asia (ASIA), Other Branches of Umbrella Group (OBU) and other regions achieve the peak later between 2050 and 2060; India (IND), the Middle East and Africa (MAF) and other regions in some scenarios (such as SSP2 scenario) are the last to arrive peak (between 2060 and 2080), indicating that after the middle of this century, these regions will contribute more to world cement emissions. It is found that in 2070, 52.3% of the world's cement production process-related CO_2 emissions will be produced in India (IND) and the Middle East and Africa (MAF) in the SSP2 (medium challenge) scenario, and their effects cannot be ignored.

In summary, it is revealed that the development paths of cement production process-related CO_2 emissions in different regions under different SSPs scenarios are not the same. The results for 175 countries are given in Appendix Table A.5. The cumulative cement production process-related CO_2 emissions are ranging from 32.54 billion tons to 45.45 billion tons with largest CO_2 emissions in SSP3. And the cement production process-related CO_2 emissions of different regions under SSPs scenarios arrive peak differently and their contributions to the total amount of world cement production process-related CO_2 emissions are also diverse. Therefore, the influence of different socio-demographic pathways should be carefully considered when assessing the cement production process-related CO_2 emissions of each region.

5. Conclusions and implications

To provide a picture for global cement production process-related CO_2 emissions in future, this study enriches the existing research to project the cement production process-related CO_2 emissions in 175 countries from 2015 to 2100, with specific consideration of the dynamic socio-economic development contexts depicted by Shared Socioeconomic Pathways (SSP1-SSP5). The cement production process-related CO_2 emissions in 175 countries under five SSP scenarios are estimated in this study. It can provide more evidence for the future trend of industrial process-related CO_2 emissions and better support the existing integrated assessment models that mainly account for the greenhouse gas caused by energy consumption and non-energy consumption related to land use.

The results showed that the largest amount of global cumulative cement process-related CO_2 emissions would be 45.45 billion tons under SSP3 scenario (further fragmentation between regions) which describe a scenario of high challenge both in mitigation and adaption scenario, and following are SSP2 (a more middle-of-the-road development pattern) and SSP1 (a green growth strategy) scenarios. The countries that contribute the most to the global cumulative cement production process-related CO_2 emissions from 2015 to 2100 are India, China, Nigeria, United States of America and Pakistan under the SSP1-SSP5 scenarios.

The development paths of cement process-related CO_2 emissions are quite different in 12 regions under different SSP scenarios. It can be mainly divided into three types: the downward trend, the rising trend and the trend of rising first and then declining. For example, the emissions of Japan (JPN) and the European Union (EU) show a clear downward trend under five scenarios but the emissions of Asia (ASIA), Latin America (LAM), the Middle East and Africa (MAF) show an upward trend in the SSP3 scenario. In addition to Japan (JPN) and the European Union (EU), other countries and regions experience the trend of rising first and then declining under different scenarios, but the peak time and the changing rates are quite different. Therefore, it is very necessary to consider the development modes and specific impact of different socioeconomic pathways when assessing the cement production process-related CO_2 emissions and making the emission reduction policies in the future.

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Appendix

Table A.1
Calculation system of carbon dioxide process-related emissions from cement production

Published Agencies and Reports	Published Time	Methods Descriptions
IPCC 'Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories'	1996	For the countries, three methods were provided for calculating the CO_2 emissions from the raw material (carbonate) for cement production. It does not involve fuel combustion and indirect emissions. However, the calculation of fixed source combustion and mobile source combustion was described meticulously in its energy section.
IPCC '2006 IPCC Guidelines for National Greenhouse Gas Inventories'	2006	
WRI/WBCSD	2001 First Edition	For the enterprises, the methods were presented for providing a set of corporate CO_2 emissions organization boundaries and operational boundaries and putting forward the

Table A.1 (*continued*)

Published Agencies and Reports	Published Time	Methods Descriptions
'Greenhouse Gas Protocol,GHG Protocol'	2004 Revised Edition	operating boundaries 'scope' concept. Guidance documents and spreadsheets for the calculation of direct emissions and indirect emissions of carbon dioxide from cement production were provided on its website.
WBCSD-CSI	2001 First Edition	For the enterprises, the operating boundary covered all direct emissions of carbon dioxide and major indirect emissions in the cement production process, including absolute emissions and unit emissions. It provided a guidance document and a spreadsheet to help cement companies prepare carbon dioxide emissions inventories.
'Protocol of carbon dioxide emissions reduction for cement industry'	2005 Second Edition	
Australian Cement Association Protocol on Greenhouse Gas Management	1998	The calculation standard was made up of four cement companies that make up the Australian Cement Association, which only calculated the raw material calcination, fuel combustion and power use, and used the agreed emission factors.
Guidelines for the calculation of greenhouse gas emissions in Japan	2003	Formulated by the Japanese government, the method of WRI was used to determine CO_2 emission operating boundary, and each range was calculated by the method of CSI according to the actual situation in Japan.
The European Union Guidelines for The Monitoring and Reporting of Greenhouse Gas Emissions	2004	For the EU member, it provided detailed carbon dioxide emissions data, emission factors and oxidation conversion rate for the energy industry and the manufacturing industry including the cement industry.
United States Environmental Protection Agency. Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance: Direct Emissions from Stationary Combustion Sources	2005	For the 'Climate Leadership cooperation program' project, it provided detailed guidance and reports on cement production, direct emissions and indirect emissions of CO_2 on its Web site and the operational boundaries were based on the method of WRI.
China Building Material Academy 'Calculation method of CO_2 emissions from cement production (draft for solicitation)'	2011	For the Chinese enterprises, it integrated IPCC and CSI methods to determine the operational boundaries of cement production. The enterprise could select the calculation method according to the actual measurable data with the use of IPCC and CSI carbon emissions coefficient.

Table A.2
The panel data unit root test results

Variable	Levels			First difference		
	LLC	ADF	PP	LLC	ADF	PP
$\ln(c_{it})$	2.275	17.825	15.476	-25.629^{***}	789.811^{***}	1879.61^{***}
$\ln(y_{it})$	15.590	0.464	0.083	-15.796^{***}	411.888^{***}	656.618^{***}

Notes: For all tests, the test statistics are reported.
***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Table A.3
The panel cointegration test results

Panel PP-statistic (weighted)	Panel ADF-statistic (weighted)	Group PP-statistic	Group ADF-statistic
-2.224^{**}	-1.648^{**}	-3.017243^{**}	-2.611^{**}

Notes: For all tests, the test statistics are reported.
***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Table A.4
175 countries in 12 regions

Region	Involved countries
USA	United States of America
CHN	China
JPN	Japan
RUS	Russian Federation
IDN	India
OBU (Other Branches of Umbrella Group)	Canada, Australia, New Zealand
EU (European Union)	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom, Cyprus, Czech Republic, Estonia, Hungary, Malta, Poland, Slovakia, Slovenia, Bulgaria, Latvia, Lithuania, Romania, Croatia
OWE (Other West European Developed Countries)	Albania, Montenegro, Serbia, The former Yugoslav Republic of Macedonia, Turkey, Bosnia and Herzegovina, Guam, Iceland, Liechtnstein, Norway, Puerto Rico, Switzerland,
EES (Eastern European CIS excluding Russian Federation)	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
ASIA (Asia excluding China, India, Japan)	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, Fiji, French Polynesia, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam
MAF (Middle East and Africa)	

(*continued on next page*)

Table A.4 (*continued*)

Region	Involved countries
	Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe
LAM (Latin America)	Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela (Bolivarian Republic of)

Note: There are 190 countries (or areas) in the table and they are divided into 12 regions based on comprehensive consideration of SSP area division and emission reduction subject's development characteristics and emission reduction intention. However, because of the lack of GDP and population data of 15 countries in SSP database, 175 countries are finally selected as research objects. The excluded countries or areas include Montenegro, Guam, Liechtnstein, Micronesia (Fed. States of), Taiwan, Mayotte, Réunion, South Sudan, Western Sahara, Aruba, French Guiana, Grenada, Guadeloupe, Martinique and United States Virgin Islands.

Table A.5
Cumulative cement production process-related CO_2 emissions of nations

Nation	SSP1	SSP2	SSP3	SSP4	SSP5
Afghanistan	238.23	300.64	271.24	203.84	209.11
Albania	14.78	16.04	18.72	14.55	13.38
Algeria	215.98	249.69	302.73	223.47	195.16
Angola	181.39	211.53	190.51	250.30	169.81
Argentina	196.75	234.69	329.36	217.42	168.78
Armenia	11.44	12.47	15.17	11.12	9.68
Australia	135.75	147.03	119.57	119.70	142.61
Austria	36.86	35.65	31.21	32.16	37.23
Azerbaijan	50.34	55.63	58.21	48.81	48.22
Bahamas	1.88	2.22	2.64	1.91	1.73
Bahrain	12.77	14.91	16.50	13.54	13.05
Bangladesh	706.16	779.02	751.90	434.70	637.43
Barbados	1.19	1.33	1.52	1.18	1.08
Belarus	34.95	39.14	46.56	35.18	31.35
Belgium	53.77	51.28	44.61	45.17	55.37
Belize	1.80	2.22	3.01	2.57	1.46
Benin	69.04	76.39	52.98	36.86	64.76
Bhutan	4.32	5.25	7.37	5.06	3.91
Bolivia (Plurinational State of)	52.41	67.47	101.52	92.32	43.11
Bosnia and Herzegovina	15.59	16.49	17.87	15.07	14.71
Botswana	11.94	14.03	14.26	11.02	11.08
Brazil	985.29	1183.74	1402.63	1048.62	873.85
Brunei Darussalam	1.64	2.02	2.57	1.78	1.42
Bulgaria	27.51	30.59	36.13	28.12	25.23
Burkina Faso	135.30	166.25	130.96	93.28	119.80
Burundi	55.86	55.17	26.02	16.08	58.75
Cambodia	63.74	76.12	87.52	52.07	53.14
Cameroon	126.57	145.00	145.59	127.51	115.28
Canada	207.52	202.72	146.33	174.00	207.28
Cape Verde	2.22	2.63	3.53	2.31	1.70
Central African Republic	23.13	23.20	11.47	6.10	22.63
Chad	88.68	103.18	77.98	65.17	79.56
Chile	82.64	94.31	121.95	87.74	73.77
China	5020.82	5776.22	6953.22	5218.95	4419.14
Colombia	266.75	323.25	415.64	292.16	235.39
Comoros	3.64	4.58	3.84	2.49	3.21
Congo	32.18	39.22	46.31	46.28	29.46
Costa Rica	28.76	34.27	41.79	32.23	26.75
Côte d'Ivoire	107.61	134.32	183.52	156.94	87.07
Croatia	19.55	21.32	23.27	18.80	18.55
Cuba	40.15	41.83	47.14	38.56	35.53
Cyprus	7.40	8.36	8.61	7.27	7.30
Czech Republic	46.55	45.44	39.97	40.41	46.97
Democratic Republic of the Congo	491.17	520.35	323.98	178.26	461.26
Denmark	29.69	28.71	24.49	24.26	30.86
Djibouti	5.57	6.13	6.41	6.36	5.18
Dominican Republic	56.19	67.31	91.58	59.59	48.22
Ecuador	82.65	100.01	136.63	92.26	71.56
Egypt	509.80	616.05	801.89	532.60	445.85
El Salvador	24.75	28.96	42.49	24.44	17.90
Equatorial Guinea	5.16	6.50	8.39	7.88	4.67
Eritrea	30.93	23.46	5.21	1.39	34.66
Estonia	5.77	5.49	4.98	4.98	5.81
Ethiopia	538.36	622.70	489.71	315.43	488.44
Fiji	3.44	4.30	5.00	3.04	2.72
Finland	27.26	26.61	22.85	22.38	27.98

Table A.5 (*continued*)

Nation	SSP1	SSP2	SSP3	SSP4	SSP5
France	353.46	363.97	326.43	310.90	358.57
French Polynesia	1.63	1.91	2.39	1.62	1.45
Gabon	9.65	11.30	14.64	14.01	8.45
Gambia	11.84	14.24	14.59	11.56	10.17
Georgia	14.01	15.50	20.63	13.95	11.37
Germany	331.99	325.25	286.94	289.07	330.69
Ghana	170.66	210.85	211.64	170.17	152.83
Greece	50.74	50.50	46.64	46.27	50.43
Guatemala	90.29	120.98	162.77	136.62	74.74
Guinea	52.11	65.80	78.11	59.46	38.48
Guinea-Bissau	8.25	9.42	7.70	5.91	7.31
Guyana	2.77	3.18	4.25	2.79	2.06
Haiti	43.65	46.03	45.48	32.28	35.36
Honduras	42.78	53.45	67.71	57.42	35.96
Hungary	44.22	41.97	37.33	38.90	45.12
Iceland	1.93	1.88	1.66	1.66	1.99
India	6720.44	8234.58	9305.62	7278.37	6066.38
Indonesia	1119.56	1341.22	1542.80	1154.19	981.83
Iran (Islamic Republic of)	417.81	463.81	568.01	422.42	368.31
Iraq	284.83	351.85	465.43	520.74	254.69
Ireland	27.25	25.91	22.50	22.80	28.11
Israel	61.02	64.48	55.62	53.57	65.96
Italy	280.15	282.86	250.24	256.08	283.71
Jamaica	11.53	13.40	18.06	11.58	9.03
Japan	459.69	477.80	439.76	404.38	438.77
Jordan	54.83	66.56	80.08	80.66	52.11
Kazakhstan	86.53	102.35	122.27	84.55	74.95
Kenya	290.58	325.10	316.49	234.74	260.80
Kuwait	14.99	18.38	20.16	13.53	12.95
Kyrgyzstan	23.93	27.19	33.62	20.76	20.10
Lao People's Democratic Republic	32.51	39.70	47.40	40.02	27.91
Latvia	8.12	8.99	10.36	8.13	7.32
Lebanon	20.81	23.43	29.93	21.40	18.63
Lesotho	9.38	10.11	9.06	7.41	8.39
Liberia	38.22	43.02	22.25	17.86	40.05
Libyan Arab Jamahiriya	38.41	45.33	61.99	42.18	32.96
Lithuania	12.28	13.22	16.53	12.08	10.77
Luxembourg	2.65	2.55	1.94	2.36	2.89
Madagascar	137.16	165.18	128.21	86.94	131.79
Malawi	136.87	168.75	134.62	84.46	123.66
Malaysia	169.49	201.18	271.69	178.94	148.96
Maldives	1.95	2.29	2.72	2.06	1.76
Mali	119.71	134.76	83.96	56.54	109.28
Malta	1.80	1.96	2.22	1.74	1.66
Mauritania	23.45	28.39	29.50	29.72	22.53
Mauritius	5.83	6.97	8.76	6.53	5.19
Mexico	597.78	733.62	1047.95	645.51	498.66
Mongolia	14.43	17.63	23.99	15.34	12.42
Morocco	144.92	170.14	241.14	163.23	119.37
Mozambique	140.21	163.46	115.36	79.32	126.45
Myanmar	168.73	158.31	115.03	58.28	162.43
Namibia	15.33	16.97	19.30	19.04	14.03
Nepal	162.71	173.77	127.60	76.51	153.94
Netherlands	75.62	73.24	66.99	66.31	76.26
New Caledonia	1.61	1.96	2.28	1.59	1.47
New Zealand	26.23	26.87	23.53	23.12	27.12
Nicaragua	24.57	29.69	41.11	23.38	18.74
Niger	157.15	214.43	124.81	66.91	145.27
Nigeria	1501.98	1883.10	2099.08	1797.14	1323.66
Norway	26.96	27.14	22.06	21.93	28.41
Occupied Palestinian Territory	20.76	26.09	47.17	32.39	16.10
Oman	15.09	21.34	27.74	17.11	13.83
Pakistan	1300.82	1599.34	1554.64	1271.57	1186.28
Panama	18.44	22.22	31.08	20.41	16.02
Papua New Guinea	41.66	51.40	58.06	52.85	37.60
Paraguay	37.71	46.71	61.67	59.10	32.63
Peru	130.10	159.21	237.06	144.79	103.72
Philippines	597.88	713.50	832.33	727.16	538.31
Poland	170.10	164.46	149.32	149.29	168.61
Portugal	55.18	54.54	47.39	50.24	57.64
Puerto Rico	13.26	14.30	20.15	13.24	10.48
Qatar	7.63	7.83	7.72	5.95	4.78
Republic of Korea	162.81	157.28	150.11	141.91	153.91
Republic of Moldova	9.04	9.53	12.65	8.69	7.21
Romania	77.09	86.67	104.25	79.45	68.77
Russian Federation	579.44	664.35	750.24	574.43	520.74

(*continued on next page*)

Table A.5 (*continued*)

Nation	SSP1	SSP2	SSP3	SSP4	SSP5
Rwanda	83.47	96.01	71.84	51.81	78.05
Samoa	0.64	0.74	1.18	0.74	0.43
Saudi Arabia	221.33	265.82	330.05	312.97	200.70
Senegal	77.87	105.07	106.23	80.05	66.37
Serbia	46.38	49.48	50.69	44.86	46.36
Sierra Leone	39.24	41.90	26.11	18.68	38.75
Singapore	18.85	19.60	20.76	18.36	17.58
Slovakia	24.79	23.62	21.29	21.67	24.80
Slovenia	10.26	9.89	8.43	8.96	10.74
Solomon Islands	3.59	4.38	4.66	4.15	3.29
Somalia	18.86	7.13	0.19	0.00	19.28
South Africa	295.83	320.85	355.10	274.89	278.64
Spain	249.82	251.65	217.05	229.19	260.17
Sri Lanka	96.13	116.71	148.52	105.40	82.77
Sudan	334.27	429.26	436.02	294.48	303.70
Suriname	2.69	3.25	4.35	2.92	2.33
Swaziland	6.63	7.05	6.79	6.05	6.01
Sweden	52.96	52.01	42.86	43.41	56.27
Switzerland	34.19	34.08	30.17	30.32	34.26
Syrian Arab Republic	131.45	164.25	227.01	217.54	113.80
Tajikistan	29.27	34.23	47.40	31.71	20.06
Thailand	296.51	337.64	418.88	314.56	271.42
The former Yugoslav Republic of Macedonia	10.65	11.62	12.64	10.64	10.25
Timor-Leste	6.28	9.24	13.19	5.49	3.87
Togo	34.84	35.58	22.03	14.99	32.63
Trinidad and Tobago	4.91	5.44	7.01	4.89	4.22
Tunisia	53.69	60.05	74.67	53.75	47.88
Turkey	392.59	465.68	654.08	454.54	349.60
Turkmenistan	26.27	29.29	36.87	24.93	21.50
Uganda	330.68	439.89	405.67	306.32	294.32
Ukraine	172.88	195.48	214.39	173.13	161.84
United Arab Emirates	48.85	57.27	60.59	49.18	45.16
United Kingdom of Great Britain and Northern Ireland	317.31	325.26	286.12	276.45	323.00
United Republic of Tanzania	355.39	458.40	431.45	335.88	315.32
United States of America	1496.26	1596.64	1297.82	1301.15	1526.25
Uruguay	13.39	15.80	21.68	14.65	11.31
Uzbekistan	136.90	156.50	190.27	131.80	116.73
Vanuatu	1.57	2.03	2.45	2.29	1.38
Venezuela (Bolivarian Republic of)	182.39	212.64	267.20	196.02	155.95
Viet Nam	424.59	467.19	520.33	419.03	387.85
Yemen	200.18	248.07	256.39	229.71	193.58
Zambia	108.70	139.56	157.24	126.90	94.52
Zimbabwe	35.45	34.75	31.31	20.52	24.98

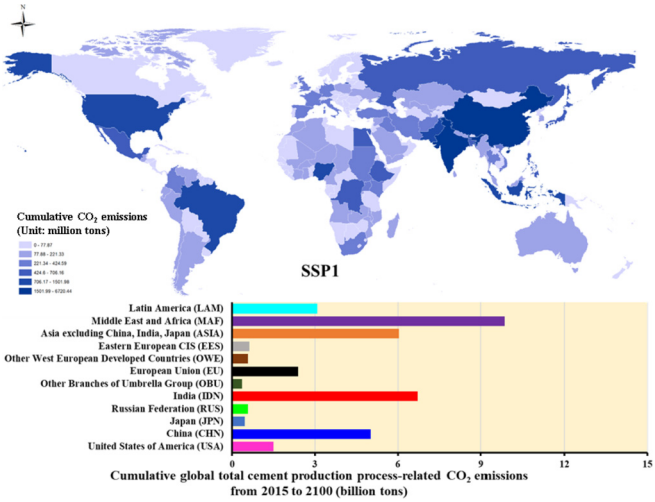

Fig. A.1. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP1 scenario Note: Both the map and bar chart are showing the cumulative cement production process-related CO_2 emissions in the study SSP. Map is for 175 countries and bar chart is for 12 regions.

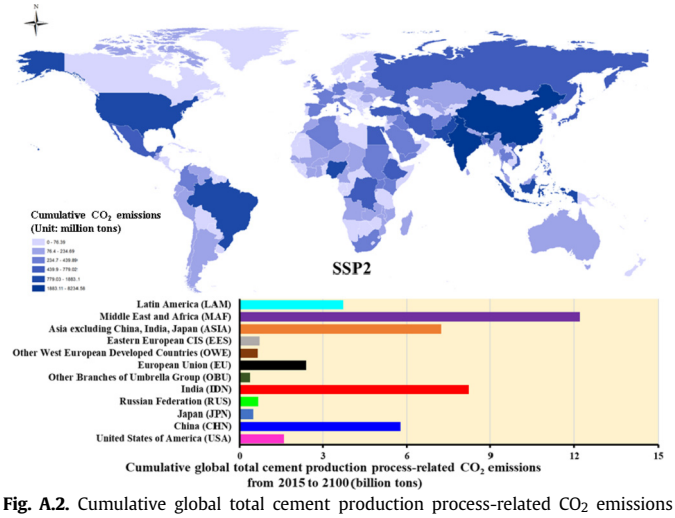

Fig. A.2. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP2 scenario. Note: Both the map and bar chart are showing the cumulative cement production process-related CO_2 emissions in the study SSP. Map is for 175 countries and bar chart is for 12 regions.

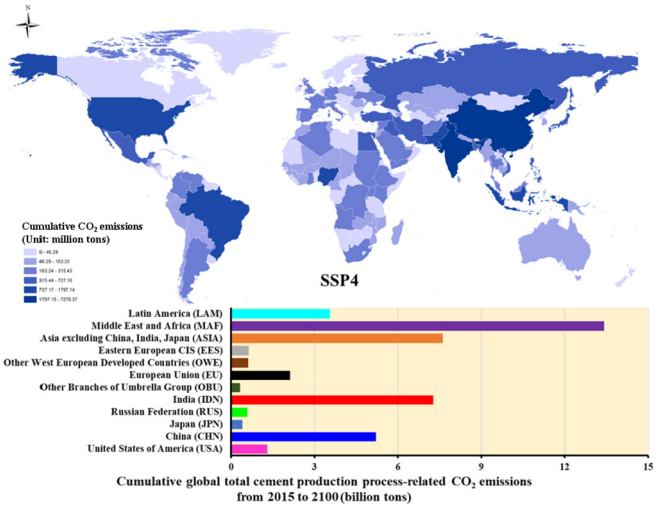

Fig. A.3. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP4 scenario. Note: Both the map and bar chart are showing the cumulative cement production process-related CO_2 emissions in the study SSP. Map is for 175 countries and bar chart is for 12 regions.01

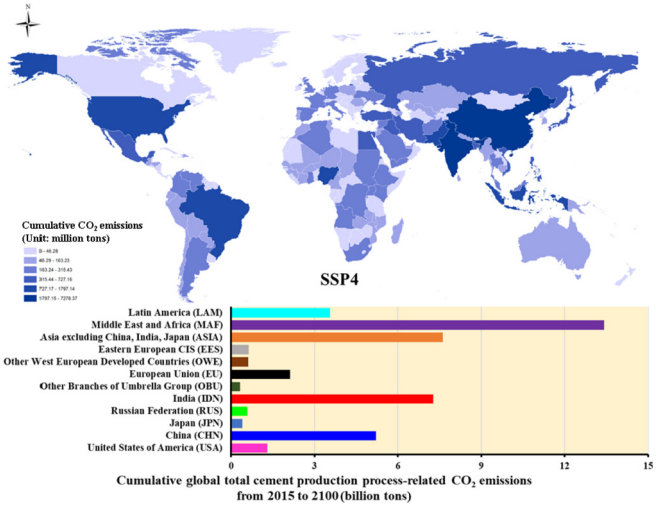

Fig. A.4. Cumulative global total cement production process-related CO_2 emissions from 2015 to 2100 in SSP5 scenario. Note: Both the map and bar chart are showing the cumulative cement production process-related CO_2 emissions in the study SSP. Map is for 175 countries and bar chart is for 12 regions.

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